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# The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging)

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Benthic recolonization was investigated at a site historically used for the extraction of marine sand and gravel. The main objective was to assess the effects of different levels of dredging intensity on the recolonization of benthic fauna and sediments. Preliminary observations from this study indicated that the fauna within an area of seabed exposed to high dredging intensities remained in a perturbed state some 4 years after the cessation of dredging. Thereafter, annual monitoring surveys of the benthos and sediments at the "treatment" and "reference" sites have followed the recolonization process. Results from univariate and multivariate data analyses show that distinct differences in the nature of assemblages at sites exposed to high and lower levels of dredging intensity persist at least 6 years after the cessation of dredging. This paper presents the physical and biological findings 6 years after dredging, together with a generic framework for evaluating post-cessation recolonization studies.



Keywords: aggregate extraction, dredging, impacts, North Sea, recolonization.

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## Introduction

Much of the seabed surface around the England and Wales coastline consists of coarse material, i.e. various proportions of sand and gravel (CIRIA, 1996). Where these resources are present in sufficient quantity, are of the right composition, and are accessible to commercial dredgers, they may be exploited as a source of aggregate for the construction industry, to supplement land-based sources, or as a source of material for beach nourishment (Singleton, 2001).

As the extraction of marine sand and gravel has its primary impact at the seabed, assessment of the effects of this activity has conventionally targeted bottom substrata and the associated benthic fauna (Millner *et al.*, 1977; Desprez, 2000; Van Dalfsen *et al.*, 2000). Historically, the scientific study of coarser substrata has presented a significant challenge, largely on account of the difficulties of obtaining reliable quantitative samples (Eleftheriou and Holme, 1984). As a consequence, information on the nature and distribution of benthic assemblages, and on their wider role in the marine ecosystem, is considerably more limited than in areas of soft sediments.

Of those studies which have considered the effects of marine aggregate extraction, most have concentrated on establishing the rates and processes of macrobenthic recolonization upon cessation of dredging (Cressard, 1975; Kenny *et al.*, 1998; Desprez, 2000; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000; Van Dalfsen and Essink, 2001). These studies indicate, typically, that dredging causes an initial reduction in the abundance, species diversity, and biomass of the benthic community (for review see Newell *et al.*, 1998) and that substantial progress towards full restoration of the fauna and sediments can be expected within a period of approximately 2–4 years following cessation (Kenny *et al.*, 1998; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000; Van Dalfsen and Essink, 2001). For example, Van Dalfsen *et al.* (2000) suggested that recolonization of a dredged area by polychaetes occurred within 5–10 months after the cessation of dredging in a site located within the North Sea, with restoration of biomass to pre-dredge levels anticipated within 2–4 years. Such studies have been mainly concerned with the effects of dredging operations conducted over a relatively short time scale, e.g. up to periods of 1 year (Kenny *et al.*, 1998; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000; Van Dalfsen and

Essink, 2001). Under such circumstances, any more subtle effects, e.g. on seasonal recruitment success to the locality, arising from prolonged dredging over several years would clearly be expected to be minimal. Few studies have addressed the consequences of long-term dredging operations (Desprez, 2000). Thus, there is limited information which is directly applicable to the impacts of commercial dredging operations in UK waters where the life-time of a typical production licence is at least 15 years. The aim of this study was to assess the status of the seabed substrata and associated benthic assemblages at a former extraction site which was intensively dredged over a 25-year period. Preliminary observations on the status of this extraction site, 4 years after the cessation of dredging, were reported in Boyd *et al.* (2003). In this paper we examine the findings from surveys carried out between 2000, and 2002 i.e. 4, 5, and 6 years on, and investigate whether different historical levels of dredging intensity affect the subsequent rate and nature of benthic recolonization at an aggregate extraction site following cessation of dredging.

# Methods

## Study site

A full description of the study site (designated "Area 222") together with an account of the dredging history is reported in Boyd *et al.* (2003). It is located approximately 20 miles east of Felixstowe off the southeast coast of England (Figure 1) in water depths of between 27-m and 35-m Lowest Astronomical Tide (LAT). The tidal ellipse in the region is rectilinear and is aligned in a NNE-SSW direction which is thought to be modified by an adjacent deeper channel that encroaches into the northern edge of the extraction site. Maximum spring tidal current velocities reach 1.5 m s$^{-1}$ and there is evidence for a NNE nearbed residual tidal direction (Boyd *et al.*, 2003). This site, with dimensions of approximately 900 m by 300 m, was first licensed for sand and gravel extraction in 1971, with a peak in extraction activity recorded as 872 000 t in 1974. Extraction continued at levels $>100\,000$ t per annum until 1995, before the site was relinquished by the industry in 1996. At this site, the sand:gravel ratios of dredged cargoes were adjusted by screening, with excess sand being discharged overboard at the site of dredging.

## Sampling design

Since 1993, every vessel dredging on a Crown Estate licence in the UK has been fitted with an Electronic Monitoring System (EMS) which automatically records the date, time, and position of all dredging activity, every 30 s, to disk. EMS information was interrogated in order to locate areas of the seabed within the Area 222 extraction licence which had been subjected to different levels of dredging intensity. Replicate samples of the macrofauna and sediments were collected from areas representing two different levels as follows (i) $>10$ h of dredging within a 100-m by 100-m block during 1995 and (ii) $<1$ h of dredging within a 100-m by 100-m block during 1995. EMS data from 1995 were chosen since this year was the last year that the licensed extraction site was dredged

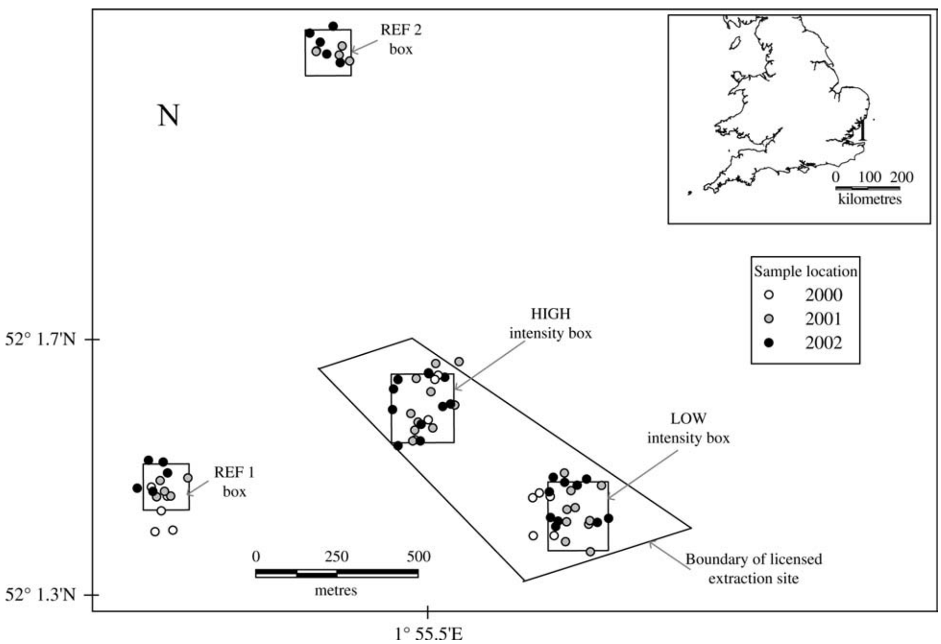


Figure 1. Map showing the location of the Area 222 extraction licence and sample locations from 2000 to 2002 in the southern North Sea.

heavily. The location and intensity of dredging was comparable between 1993 and 1995. In addition, a reference site (Reference site 1) was sampled in 2000–2002 and this was augmented by sampling at a second reference site (Reference site 2) in 2001 and 2002. Boyd *et al.* (2003) present an account of the design in terms of the likely dredging impact. Stations were randomly distributed within each area ("stratified random sampling") and allocated in proportion to the size of the sampling box (Green, 1979). Reference sites were selected as being representative of the wider environment surrounding the extraction site and outside the influence of any potential effects on the benthos from dredging (see Figure 1). Selection of appropriate reference sites was aided by the use of sidescan sonar and video images of the seabed (see Boyd *et al.*, 2003 for methodology) and following criteria given in CSTT guidelines (1997) and Boyd (2002). There was also no evidence of the effects of other forms of seabed disturbance at the reference locations, i.e. effects of trawling activity. Data arising from this design provide a comparative evaluation of "treatment" and "reference" groups (e.g. Skalski and McKenzie, 1983). Note that the "reference" areas are not necessarily representative of baseline conditions, as there is insufficient historical information on which to determine what actually constitutes the likely pre-dredging status of Area 222.

Area 222 was not dredged in the 4 years prior to sampling. Sampling was conducted in July 2000, 2001, and 2002, that is 4, 5, and 6 years after the cessation of dredging. Sampling details for locations sampled as part of this study are presented in Table 1.

## Sample collection

Samples for analysis of the macrobenthic fauna and sediment particle size were collected with a 0.1-m$^2$ Hamon grab from RV "Cirolana". This device was employed because it has been shown to be particularly effective on coarse substrata (Kenny and Rees, 1994, 1996; Seiderer and Newell, 1999).

Following estimation of sample volume, a 500-ml subsample was removed for laboratory sediment particle size analysis. The whole sample was then washed over 5-mm and 1-mm square mesh sieves to remove the fine sediment. The two resultant fractions (1–5-mm and >5-mm) were back-washed into separate containers and fixed in 4–6% buffered formaldehyde solution (diluted in seawater) with the addition of "Rose Bengal", a vital stain.

Macrofauna samples were processed according to the guidelines given in Boyd (2002). The >5-mm sample fraction was first washed with freshwater over a 1-mm mesh sieve in a fume cupboard, to remove excess formaldehyde solution, then back-washed onto a plastic sorting tray. Specimens were removed and identified, where possible, to species level. The 1-5-mm fraction was first washed over a 1-mm sieve then back-washed into a 10-litre bucket. The bucket was filled with freshwater and the sample was then gently stirred in order to separate the animals from the sediment. Once the animals were in suspension, the sample was decanted over a 1-mm mesh sieve. This process was repeated until no more material was recovered. Specimens from this fraction were placed into labelled petri dishes for identification and enumeration. The sediment was then placed on plastic trays and examined under an illuminated magnifier for any remaining animals such as bivalves not recovered in the decanting process, which were then added to the petri dishes.

## Sediment particle size analysis

The sediment subsamples from each grab were analysed for their particle size distributions. Samples were first wet-sieved on a 500-μm stainless steel test sieve using a sieve shaker. The <500-μm sediment fraction passing through the sieve, was allowed to settle from suspension in a container for 48 h. The supernatant was then removed

Table 1. Sampling details for locations sampled as part of the time-series investigations at Area 222. Box coordinates given as positions in WGS 84 from top right and bottom left hand corners of the sampling box.

| | | Box coordinates | | | Number of samples collected | | |
|---|---|---|---|---|---|---|---|
| Treatment | Code | Longitude | Latitude | Area (m$^2$) | 2000 | 2001 | 2002 |
| High intensity box | HIGH '00 to '02 | 52° 01.686′N<br>52° 01.572′N | 01° 55.554′E<br>01° 55.386′E | 40 000 | 5 | 10 | 10 |
| Low intensity box | LOW '00 to '02 | 52° 01.506′N<br>52° 01.392′N | 01° 55.968′E<br>01° 55.806′E | 40 000 | 5 | 10 | 10 |
| Reference site 1 | REF1 '00 to '02 | 52° 01.530′N<br>52° 01.470′N | 01° 54.828′E<br>01° 54.726′E | 20 000 | 5 | 5 | 5 |
| Reference site 2 | REF2 '01 to '02 | 52° 02.256′N<br>52° 02.184′N | 01° 55.278′E<br>01° 55.158′E | 20 000 | 0 | 5 | 5 |

using a vacuum pump and the remaining <500-μm sediment fraction was washed into a petri dish, frozen for 12 h, and freeze-dried. The total weight of the freeze-dried fraction was recorded. A subsample of the <500-μm fraction was then analysed using a laser sizer and a percentage weight for each size class was calculated. The >500-μm fraction was washed from the test sieve into a foil tray and oven dried at ~90°C for 24 h. It was then dry sieved on a range of stainless steel test sieves, placed at 0.5-phi intervals, down to 1 phi (500 μm). The sediment on each sieve was weighed to 0.01 g and the values recorded. The results from these analyses were combined to give a full particle size distribution for each sample.

### Acoustic surveys

Sidescan sonar surveys were undertaken using the Datasonics™ SIS 1500 digital chirps system using the Triton Isis™ data acquisition software. The Delphmap™ software package was used to post-process the data, and provided georeferenced mosaic images of the sonar data. Such surveys were undertaken in order to provide an indication of the spatial distribution of sediments in the wider area encompassing the dredged sites and to provide information on the distribution and stability of bedforms. Such information contributes to an evaluation of *inter alia* the physical "recovery" of sites, e.g. the persistence of dredged tracks or pits.

### Data analysis

#### *Sediment variables*

Particle size distribution data have been presented using cumulative frequency distribution curves. Changes in the shape of the curve for any given sample when compared to another, reflect the variations in the particle size distribution of those samples.

A correlation-based principal components analysis (PCA) was applied to ordinate results from the sediment analyses (Clarke and Warwick, 1994).

Analysis of similarities (ANOSIM, Clarke, 1993) was performed on sediment particle size data to test the significance of differences in particle size composition between treatments.

#### *Macrofaunal assemblage structure*

The total numbers of individual organisms and numbers of species were calculated for each sample group. This allows a visual interpretation of any trends (e.g. increasing or decreasing abundance at different sampling locations and over time) and their statistical significance, whereas this judgement is more difficult for results obtained by multivariate data analyses. The significance of differences between treatments was tested using one-way ANOVA.

A non-parametric multi-dimensional scaling (MDS) ordination using the Bray–Curtis similarity measure (Bray and Curtis, 1957) was applied to species abundance data.

Warwick and Clarke (1993) noted that in a variety of environmental impact studies, the variability among samples collected from impacted areas was much greater than that collected from reference sites. They suggested that this variability was in itself an identifiable symptom of perturbed situations. To test whether this pattern was evident with the data from dredged sites examined in this study, the comparative Index of Multivariate Dispersion (IMD) was calculated. IMD has a maximum value of +1 when all similarities among impacted samples are lower than any similarities among reference samples. The converse case gives a minimum for IMD of −1, and values near zero imply no difference between groups.

The comparative Index of Multivariate Dispersion is restricted to the comparison of only two groups, e.g. reference vs. high dredging intensity samples and therefore is usually complemented by calculation of the relative Index of Multivariate Dispersion (r.IMD; Somerfield and Clarke, 1997). This index has a value of 1 if the relative dispersion of samples corresponds to the "average dispersion". Values greater than 1 are obtained if replicate samples are more variable than average. In contrast, a value lower than 1 is achieved if replicate samples are less variable than average.

Analysis of similarities (ANOSIM, Clarke, 1993) was performed to test the significance of differences in macrofauna assemblage composition between samples. The nature of the groupings identified in the MDS ordinations was explored further by applying the similarity percentages program (SIMPER) to determine the contribution of individual species to the average dissimilarity between samples.

All multivariate analyses were performed using the software package PRIMER v. 5, developed at the Plymouth Marine Laboratory (Clarke and Gorley, 2001).

## Results

### Sediment characteristics

Sediment particle size characteristics are presented in Table 2 and the cumulative particle size distribution curves for each of the survey years are presented in Figure 2. Grain size descriptions relate to the Udden–Wentworth scale (Wentworth, 1922). Particle size data revealed that there was a high degree of variability between replicate samples, particularly in the gravel and sand components of the distributions.

In both 2000 and 2001, the replicate sediments sampled at the site of high dredging intensity show a large degree of variability in the gravel and coarse sand fractions. In 2002, an apparent reduction of the gravel component at this

Table 2. Mean values (±s.d.) of sediment particle size characteristics for each treatment (codes as in Table 1).

| Year | Treatment | Mean particle size [mm] | Sorting | Skewness | Kurtosis | Gravel [%] | Coarse sand [%] | Medium sand [%] | Fine sand [%] | Silt/clay [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2002 | REF1 02 | 0.54 (±0.36) | 4.71 (±0.55) | 0.28 (±0.29) | 1.77 (±0.36) | 40.78 (±7.97) | 12.16 (±2.74) | 7.85 (±5.65) | 4.92 (±1.36) | 34.30 (±10.91) |
| | REF2 02 | 2.06 (±1.56) | 3.63 (±0.97) | 0.82 (±0.77) | 3.57 (±1.36) | 51.42 (±15.59) | 19.61 (±8.73) | 6.00 (±3.43) | 4.11 (±0.70) | 18.85 (±23.64) |
| | LOW 02 | 1.23 (±0.72) | 3.44 (±0.57) | 0.58 (±0.25) | 2.97 (±0.72) | 44.35 (±9.81) | 10.34 (±4.21) | 23.48 (±6.66) | 10.57 (±3.193) | 11.27 (±7.12) |
| | HIGH 02 | 1.29 (±0.69) | 1.94 (±0.96) | 0.02 (±0.68) | 6.06 (±4.10) | 27.24 (±15.86) | 49.86 (±20.91) | 18.69 (±6.28) | 1.81 (±1.73) | 2.40 (±5.25) |
| 2001 | REF1 01 | 1.04 (±0.65) | 3.81 (±0.68) | 0.76 (±0.21) | 3.08 (±1.16) | 43.72 (±13.54) | 20.86 (±8.53) | 12.11 (±7.42) | 5.40 (±2.80) | 17.92 (±9.18) |
| | REF2 01 | 2.10 (±1.38) | 3.38 (±0.77) | 1.05 (±0.34) | 4.41 (±1.73) | 49.33 (±19.02) | 25.05 (±11.58) | 9.86 (±8.55) | 5.36 (±2.18) | 10.41 (±8.95) |
| | LOW 01 | 2.05 (±0.83) | 3.27 (±0.44) | 0.88 (±0.36) | 3.70 (±0.39) | 54.30 (±10.48) | 10.08 (±6.53) | 20.75 (±7.27) | 9.12 (±2.48) | 5.76 (±3.20) |
| | HIGH 01 | 1.41 (±1.07) | 1.83 (±1.22) | 0.55 (±0.79) | 12.87 (±10.11) | 25.36 (±24.51) | 53.25 (±29.38) | 16.20(±6.25) | 3.00 (±4.52) | 2.19 (±3.72) |
| 2000 | REF1 00 | 1.04 (±1.45) | 4.27 (±0.63) | 0.36 (±0.56) | 2.26 (±0.96) | 45.87 (±13.73) | 12.92 (±7.37) | 4.50 (±3.33) | 5.72 (±1.93) | 30.99 (±19.6) |
| | LOW 00 | 1.78 (±0.51) | 3.22 (±0.28) | 0.64 (±0.11) | 2.90 (±0.25) | 51.75 (±5.34) | 9.64 (±0.66) | 22.37 (±2.06) | 9.50 (±1.87) | 6.75 (±3.92) |
| | HIGH 00 | 1.76 (±0.91) | 1.92 (±0.89) | −0.26 (±0.86) | 4.30 (±3.03) | 34.84 (±22.70) | 40.95 (±25.60) | 20.72 (±7.42) | 2.95 (±1.99) | 0.54 (±0.63) |

location produced less variability between replicate samples. Reference site 2 was sampled in 2001 and 2002 only, and sediments from this location show more variability between replicates than those found at either Reference site 1 or the site of low dredging intensity. An ordination by PCA of sediment particle size data is illustrated in Figure 3.

In terms of particle size distribution, sediments collected from the area of low dredging intensity and the reference locations were more similar to each other than to sediments from the area of high dredging intensity. This was due to the higher percentage of coarse sand from samples collected from the area of high dredging compared with the samples from the area of low intensity and reference locations. This is reflected in the PCA ordination by the separation of the high intensity samples from the low intensity and reference samples (Figure 4). The particle size distributions of samples from within the area of low dredging intensity were also more consistent over time, as depicted by the tighter clustering of samples in the PCA ordination. In contrast, there was a much higher degree of particle size variability between replicate samples collected from the area of high dredging intensity and the reference locations, as represented by the much wider spread of samples from these locations in the PCA ordination. The separation of sediments collected from the area of low dredging intensity and the reference locations is largely on account of the higher silt/clay content of some of the reference samples (Figure 4).

In all, 70% of the total variation is explained by the first two principal components, indicating that the two-dimensional ordination gives an appropriate representation of the similarity between the collected sediments. Table 3 shows the analysis of similarities results (ANOSIM, Clarke, 1993) for particle size data between samples collected from the different treatments over the 3-year period of study. Sediments at all locations were significantly different ($p < 0.05$) from each other in terms of particle size characteristics, apart from the two reference sites in both 2001 and 2002, the site of higher dredging intensity and Reference site 2 in 2001, and the site of high dredging intensity in 2000 and Reference site 2 in 2001. Sediment characteristics differed over time at each location, although taken together these differences were not, generally, found to be statistically significant at $p < 0.05$.

## Macrofaunal assemblage structure

In all, 289 taxa were identified from the 75 Hamon grabs collected from the different treatments. Excepting values of abundance in 2002, population densities and numbers of species of macrofaunal invertebrates were significantly lower ($p < 0.05$) in the site exposed to the highest level of dredging intensity compared with the site of lower dredging intensity and reference conditions (Figure 5). In 2002, higher densities of *Pomatoceros lamarcki* (Quatrefages,

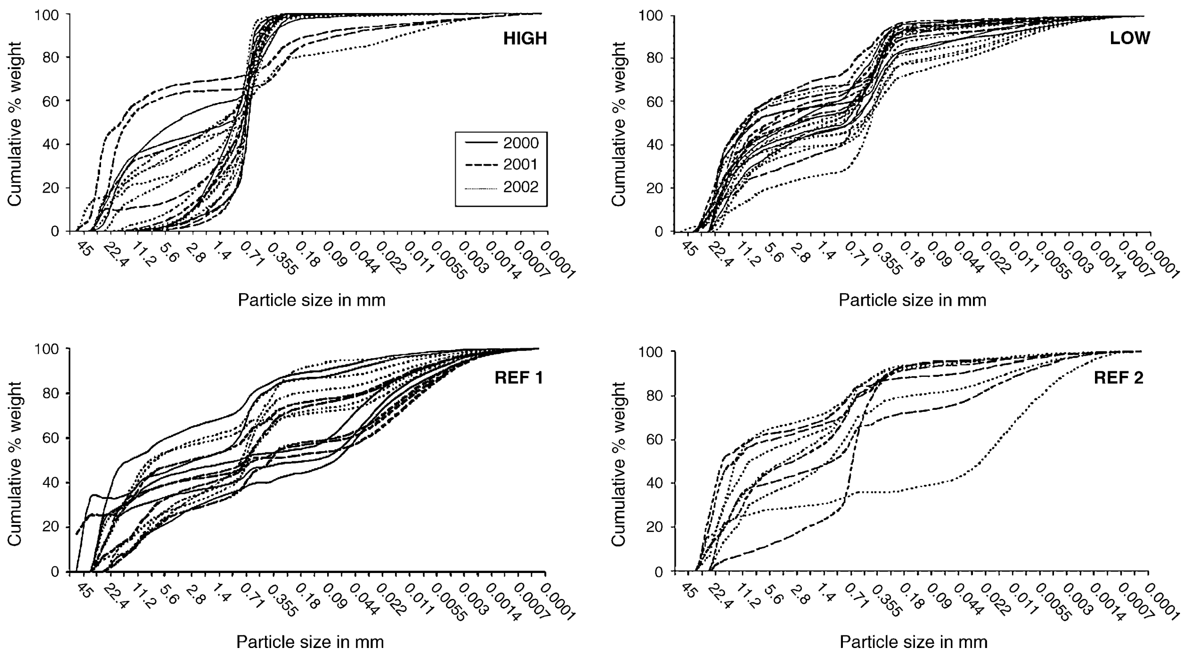


Figure 2. Sediment particle size distributions determined from replicate samples taken from sites of higher and lower levels of dredging intensity and the two references locations.

1866) recorded in one of the samples from Reference site 2 increased the variability around the mean. In this year, therefore, there was no recorded difference between the dredged sites and reference conditions in terms of population densities, although there was still a difference between sites of higher and lower dredging intensity.

In general, differences between the site of higher dredging intensity and other sample locations were due to the absence or reduced abundance ($p < 0.05$) of a range of macrofaunal species characterizing nearby sediments, including the tube worm *P. lamarki*, the pea crab *Pisidia longicornis* (Linnaeus, 1767), the polychaete *Lumbrineris gracilis* (Ehlers, 1868), and the brittle star *Amphipholis squamata* (Chiaje, 1829). Densities of these species were variable between different locations and between different years (Figure 6). Densities of *Amphipholis squamata* increased between 2000 and 2002, while densities of *Lanice conchilega* (Pallas, 1766), a sand-dwelling polychaete were significantly higher ($p < 0.05$) at all sampled sites in 2001.

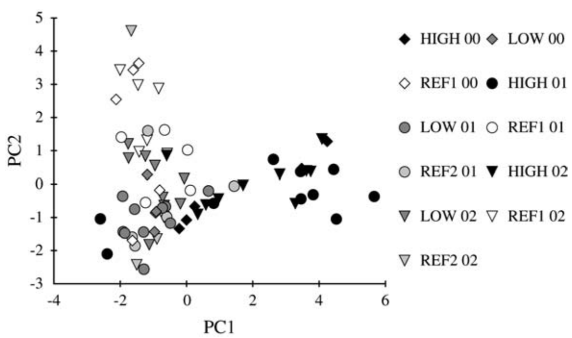


Figure 3. Two-dimensional correlation-based PCA ordination of sediment particle size data from Area 222. Total variance explained by the first two principal components = 70%. For variables involved in the ordination see Table 2.

The MDS ordination for macrofaunal assemblages collected at sites of high and lower dredging intensity and at the two reference sites is presented in Figure 7. While the reference samples and low dredging intensity samples show tight clustering of replicates, indicating a high stability of the spatial pattern, the high intensity replicate samples are much more diffusely distributed. This separation of the individual replicates from the area of high dredging intensity indicates that they are biologically dissimilar.

The comparative Index of Multivariate Dispersion (IMD) has been calculated in order to contrast the multivariate variability among samples taken from the dredged sites with samples from the reference locations (Table 4). Comparisons between the site of high dredging intensity and the reference sites and the sites of high and lower dredging intensity give the most extreme values of IMD, i.e. close to $+1$. In comparison, there is little difference between the low dredging intensity and reference samples in terms of variability in multivariate structure. Thus, a pattern of high variability in multivariate structure with

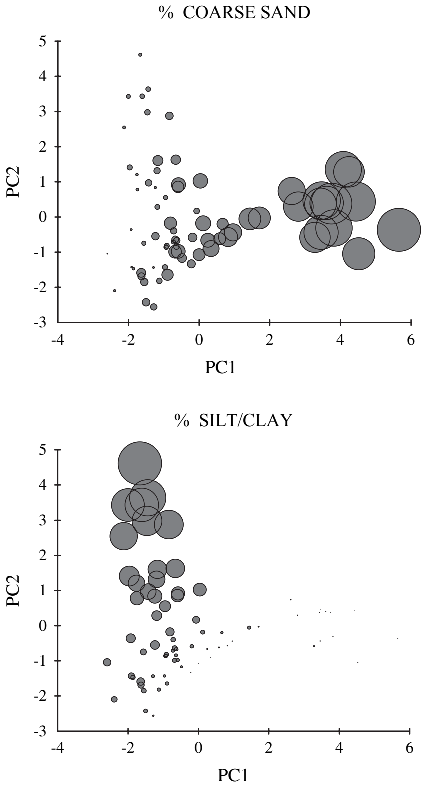


Figure 4. The same two-dimensional correlation-based PCA ordination as in Figure 3, but with superimposed circles proportional in diameter to values of percentage coarse sand and percentage silt/clay.

increased disturbance is clearly evident, in all years, at Area 222. Calculation of the relative Index of Multivariate Dispersion (r.IMD) confirms the conclusions from above, e.g. that there is an increased variability in community composition at the site of high dredging intensity in comparison with the other sampled locations (Table 5).

Macrofaunal assemblages generally discriminated well between different sampling locations in each year. ANOSIM results in Table 6 also confirm the patterns observed in the MDS ordinations. Macrofauna assemblages at all locations were significantly different ($p < 0.05$) from each other in terms of species composition, apart from the two reference sites in both 2001 and 2002, and the site of lower dredging intensity and Reference site 1 in 2001.

Further exploration of the community groupings subject to differing levels of dredging impact was undertaken using the similarity percentages program (SIMPER). Results revealed that the average similarity between replicate samples collected for each of the groups was low, particularly for samples collected from the area of high dredging intensity (see Table 7). This reflects the relatively few shared species found between replicate samples obtained from the area of high dredging intensity.

The output from SIMPER also indicates which taxa contribute the most towards similarity between replicate samples from within each of the groups. Characterizing species from each of the groups were similar over time. From the area of high dredging intensity, characterizing species tended to be infaunal species typically associated with sandy sediments. Juvenile animals also typified high intensity samples. This suggests an active process of recolonization by juvenile animals invading the dredged deposits. In contrast, those species characterizing the areas of low dredging intensity and reference areas were typically larger and included both infaunal and epifaunal species and these species represented a range of different phyla.

Information from SIMPER and ANOSIM also reveal that the differences between the area of high dredging intensity and the reference areas are more pronounced than those between the area of low dredging intensity and the

Table 3. R-values derived from the ANOSIM test for sediment particle size characteristics (mean diameter in mm, sorting coefficient, kurtosis, skewness, % gravel, % coarse sand, % medium sand, % fine sand, and % silt/clay) from locations of higher and lower dredging intensity and from two reference sites in the vicinity of Area 222 sampled in 2000–2002. Performed on normalized Euclidean distance data. Values range between ±1 and zero. A zero value indicates high similarity, and a value of ±1 indicates low similarity between samples. *Denotes significant difference at $p < 0.05$ (codes as in Table 1).

| | HIGH ’00 | LOW ’00 | REF1 ’00 | HIGH ’01 | LOW ’01 | REF1 ’01 | REF2 ’01 | HIGH ’02 | LOW ’02 | REF1 ’02 |
|---|---|---|---|---|---|---|---|---|---|---|
| HIGH ’00 | | | | | | | | | | |
| LOW ’00 | 0.480* | | | | | | | | | |
| REF1 ’00 | 0.520* | 0.592* | | | | | | | | |
| HIGH ’01 | −0.001 | 0.241* | 0.393* | | | | | | | |
| LOW ’01 | 0.502* | −0.150 | 0.650* | 0.448* | | | | | | |
| REF1 ’01 | 0.392* | 0.544* | 0.156 | 0.393* | 0.484* | | | | | |
| REF2 ’01 | 0.156 | 0.432* | 0.172 | 0.149 | 0.401* | 0.028 | | | | |
| HIGH ’02 | 0.004 | 0.447* | 0.674* | 0.067 | 0.614* | 0.400* | 0.436* | | | |
| LOW ’02 | 0.527* | −0.106 | 0.681* | 0.525* | 0.114 | 0.386* | 0.551* | 0.605* | | |
| REF1 ’02 | 0.700* | 0.912* | 0.012 | 0.436* | 0.808* | 0.160 | 0.476* | 0.703* | 0.675* | |
| REF2 ’02 | 0.268* | 0.500* | 0.004 | 0.245* | 0.452* | 0.128 | −0.160 | 0.521* | 0.609* | 0.364* |

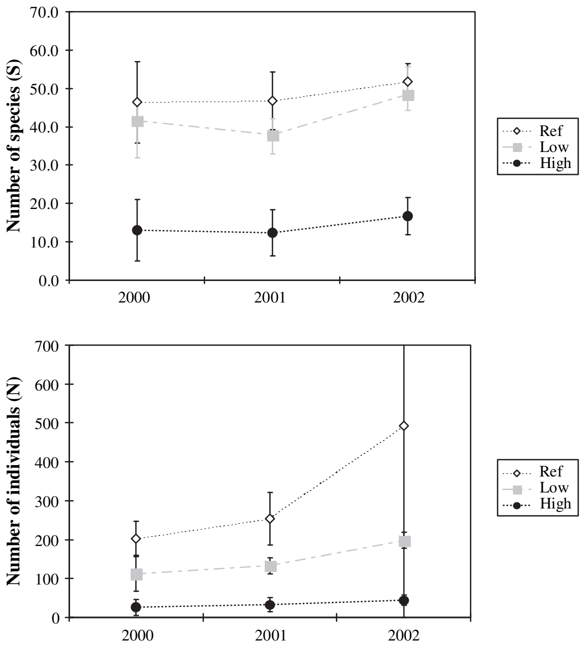


Figure 5. Means (±95% confidence intervals) of numbers of species and numbers of individuals from sites of higher and lower levels of dredging intensity and the nearby reference locations (using Reference site 1 for data arising in 2000, and data for both reference sites combined in 2001 and 2002).

reference areas. These differences in the sample groups are maintained over the 3-year period of study.

## Sidescan sonar surveys

Sidescan sonar surveys were conducted at Area 222 in 2000, 2001, and 2002. Figure 8 shows the output of the sidescan sonar survey conducted in 2002. Operational factors such as weather conditions and the acoustic resolution applied which may affect the quality of the acoustic record have been taken into account when comparing the output from the sidescan sonar surveys over time.

The substrata and seabed features within and in the vicinity of Area 222 identified from the 2001 and 2002 sidescan sonar surveys are consistent with those observed in 2000 (Boyd *et al.*, 2003). Disturbed sandy sediments interspersed with patches of sandy gravel and occasional small outcrops of consolidated clay predominate in the northern part of the extraction site. EMS records indicate that this area was subjected to the most intensive dredging activity in the years immediately prior to relinquishment, and some evidence of the effects of the trailer suction hopper dredging consistent with observations made in other studies (e.g. Diesing *et al.*, in press), remains within this part of the site (Figure 9). The sidescan sonar survey conducted in 2001 and 2002 extends to the north of the extraction site and encompasses an area of disturbed seabed previously only surveyed in part in the 2000 survey. This area of seabed to the northeast of the extraction site is uneven, consisting of a series of interconnected pits which is consistent with the effects of static suction hopper dredging (Figure 8). Thus, as noted in previous investigations, it appears that the seabed in this area has been dredged (without a licence) some time prior to the introduction of the EMS in 1993 (Boyd *et al.*, 2003). The area of disturbed seabed extends up to 1000 m away from the northern limit of the extraction site and is characterized by stable slightly muddy sandy gravels, interspersed by patches of clean rippled sand which form the base of the pit structures. Sediment transport features associated with the zone of out of area dredging also appear to extend up to 2500 m away from the northern boundaries of the former extraction site.

A number of large sand waves, whose crests run at right angles to the tidal axis, are present 150 m to the north of Area 222. The presence of these features may be the result of deposition and subsequent entrainment of screened sands produced during the dredging activity within and adjacent to Area 222. Furthermore, the sidescan sonar data indicate that those substrata surrounding Area 222 which have not been directly or indirectly affected by historic dredging activity are similar, being composed of a mixture of sand, gravel, and to a lesser extent silt with the occasional outcrop of clay. It should be noted that while sidescan sonar is effective in describing the nature of the sediment surface, it provides no information on buried substrata.

Changes in the physical status of the seabed have been assessed over the surveyed areas between 2000 and 2002. Particular attention has been given to two areas of seabed that show a persisting physical impact from historic dredging activity (Figures 9 and 10). Sidescan imaging shows little change in the nature and the distribution of the substrata over the wider survey area between 2000 and 2002. In each year, the seabed substrata surrounding the areas of dredging impact (including those found at the reference sites) are stable, mixed sediments.

Within the licensed extraction site, there appears to be some variability in the spatial distribution of sediments over time. Figure 9 shows a sidescan sonar image of the same area of seabed within and immediately surrounding Area 222, in each of the 3 survey years. These images show that while there has been some redistribution of sandy material within the licensed extraction site there has been little change in the overall amount of sand present. Trailer suction hopper dredge tracks are present within and immediately to the north of the extraction site in all years and there appears to be little modification of their appearance over the duration of these surveys (Figures 9 and 10).

# Discussion

A number of studies have attempted to identify and explain distribution trends in benthic assemblages following the

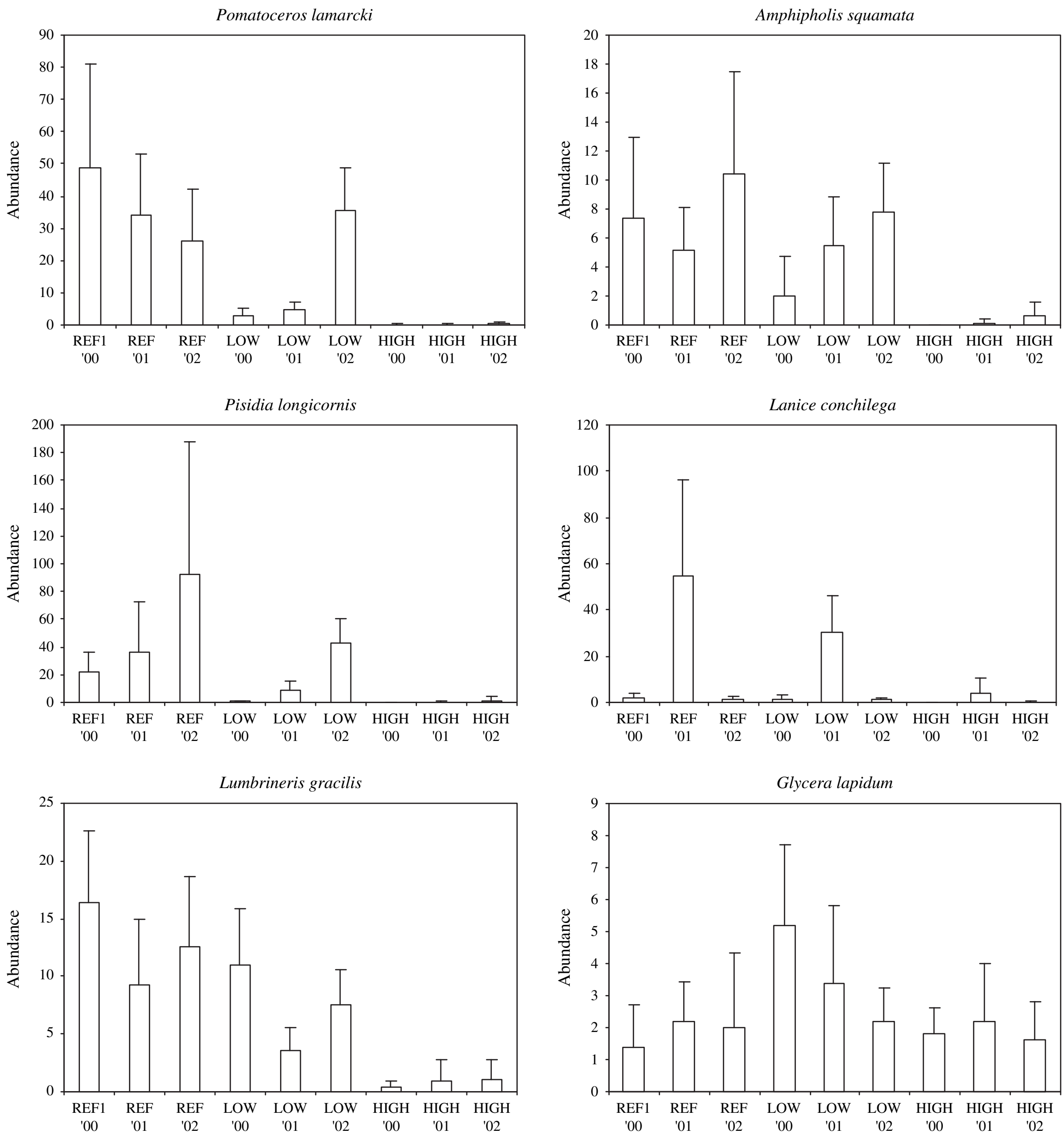


Figure 6. Means (+s.d.) of abundances of selected macrofauna species sampled in 2000–2002 at sites of high and lower levels of dredging intensity and at both reference sites (Codes as in Table 1). Data for 2000 are from Reference site 1, whereas data for 2001 and 2002 are data combined from both reference sites.

cessation of marine dredging (Cressard, 1975; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000; Van Dalfsen and Essink, 2001). Effects on the benthos and sediments identified in such studies show some parallels with the findings observed in this investigation. For example, Desprez (2000) showed that for an industrial extraction site off Dieppe, France, the structure of the benthic community changed from one of coarse sands characterized by the lancelet *Branchiostoma lanceolatum* (Pallas, 1744) to one of fine sands composed of the infaunal polychaetes *Ophelia borealis* (Quatrefages, 1866), *Nephtys cirrosa* (Ehlers, 1868), and *Spiophanes bombyx* (Claparède, 1870). Thus, the change in the assemblage structure reflected a change in sediment composition caused by dredging. Significant changes in particle size composition, resulting in a net fining of the sediment within extraction sites, have also been reported by Van Dalfsen *et al.* (2000) and Sardá *et al.* (2000) following sand extraction.

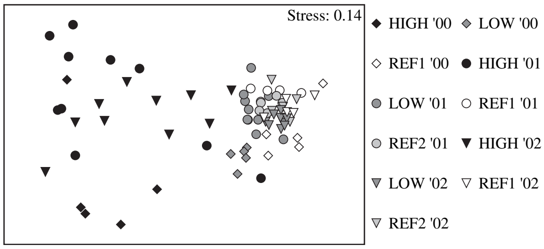


Figure 7. MDS ordination of Bray−Curtis similarities from double square-root transformed species abundance data 4, 5, and 6 years (2000−2002) after the cessation of dredging at high and lower levels of dredging intensity and at two nearby reference locations (codes as in Table 1).

At Area 222, sediments collected from the northern sector of the extraction site tended to contain proportionally more sand and less gravel than most of the other sampled sediments. This part of the extraction site is coincident with the location of intensive dredging recorded by the EMS (see also Boyd *et al.*, 2003). Sidescan sonar images of the extraction site also confirm the presence of dredge tracks within this area. Within the extraction site, screening of the dredged cargoes was undertaken to increase the gravel content with the return of finer material (usually sands) to the sea by means of a reject chute. Over time, this screening activity has the potential to significantly change the composition of sediments within a dredged area. Therefore, it is likely that, over a 25-year period of dredging, the intensively dredged areas of seabed at Area 222 have also undergone a similar transformation to those documented in the literature and thus have become sandier over time.

Table 4. Index of Multivariate Dispersion (IMD) between all pairs of conditions.

| Year | Conditions compared | IMD |
|---|---|---|
| 2000 | High/Reference site 1 | +0.94 |
| | High/Low | +1 |
| | Low/Reference site 1 | −0.04 |
| 2001 | High/Reference site 1 | +0.90 |
| | High/Low | +0.82 |
| | Low/Reference site 1 | +0.13 |
| | High/Reference site 2 | +0.96 |
| | Low/Reference site 2 | +0.51 |
| 2002 | High/Reference site 1 | +0.92 |
| | High/Low | +0.97 |
| | Low/Reference site 1 | −0.42 |
| | High/Reference site 2 | +0.88 |
| | Low/Reference site 2 | +0.63 |

Table 5. Relative Index of Multivariate Dispersion (r.IMD) in each year.

| Year | Site | r.IMD |
|---|---|---|
| 2000 | High intensity | 1.558 |
| | Low intensity | 0.708 |
| | Reference site 1 | 0.835 |
| 2001 | High intensity | 1.572 |
| | Low intensity | 0.815 |
| | Reference site 1 | 0.759 |
| | Reference site 2 | 0.462 |
| 2002 | High intensity | 1.519 |
| | Low intensity | 0.372 |
| | Reference site 1 | 0.653 |
| | Reference site 2 | 0.771 |

There is a large variability in the sediment characteristics sampled within the northern part of the extraction site. Presumably, this represents the uneven impact of the dredger draghead on the seafloor. Further evidence of the patchy nature of substrata is provided by sidescan sonar images of the dredged locations. This variability among replicate samples was also evident in biological samples collected from the area of high dredging intensity. Indeed, a high variability in the composition of sediments and benthic assemblages at dredged locations has been reported by Kenny and Rees (1994) and Sardá *et al.* (2000). Such observations lend further support to the hypothesis of Warwick and Clarke (1993), namely that variability in assemblage structure may be an identifiable symptom of perturbed conditions. In this case, however, a higher variability in assemblage structure at the extraction areas appears to be the result of increased habitat heterogeneity within the intensively dredged site which affects both the identity of species and the variation in abundances of each species. This propensity for extraction sites to exhibit variability in terms of sediment characteristics and species composition also has to be referenced against a high degree of natural variability and small-scale sediment patchiness that can be encountered in benthic ecosystems, even at locations like Reference site 2, which appear superficially to be relatively homogeneous.

In contrast to other studies that have demonstrated the rapid degradation of dredge tracks after cessation of dredging (Millner *et al.*, 1977; Kenny *et al.*, 1998), it appears that substantially longer periods, i.e. at least 9 years, are required for the complete erosion of dredge tracks in the disturbed area to the northeast of Area 222. Furthermore, the maintenance of a biological assemblage composed of juvenile animals at the site of high dredging intensity up to 6 years after cessation suggests that these species are unable to reach maturity owing to the unstable nature of sediments in the area. Thus, it appears that at the

Table 6. R-values derived from the ANOSIM test for macrofaunal assemblages (fourth root transformed) from locations of higher and lower dredging intensity and from two reference sites in the vicinity of Area 222 sampled in 2000−2002. Values range between 1 and zero. A zero value indicates high similarity, and a value of 1 indicates low similarity between samples. *Denotes significant difference at $p < 0.05$ (codes as in Table 1).

| | HIGH ’00 | LOW ’00 | REF1 ’00 | HIGH ’01 | LOW ’01 | REF1 ’01 | REF2 ’01 | HIGH ’02 | LOW ’02 | REF1 ’02 |
|---|---|---|---|---|---|---|---|---|---|---|
| HIGH ’00 | | | | | | | | | | |
| LOW ’00 | 0.832* | | | | | | | | | |
| REF1 ’00 | 0.944* | 0.868* | | | | | | | | |
| HIGH ’01 | 0.297* | 0.591* | 0.744* | | | | | | | |
| LOW ’01 | 0.985* | 0.748* | 0.744* | 0.707* | | | | | | |
| REF1 ’01 | 0.980* | 1.000* | 0.824* | 0.612* | 0.345* | | | | | |
| REF2 ’01 | 0.972* | 1.000* | 0.808* | 0.609* | 0.162 | 0.188 | | | | |
| HIGH ’02 | 0.508* | 0.480* | 0.751* | 0.190* | 0.665* | 0.596* | 0.601* | | | |
| LOW ’02 | 0.993* | 0.995* | 0.909* | 0.797* | 0.612* | 0.889* | 0.785* | 0.742* | | |
| REF1 ’02 | 0.980* | 1.000* | 0.668* | 0.754* | 0.717* | 0.536* | 0.652* | 0.614* | 0.560* | |
| REF2 ’02 | 0.980* | 0.972* | 0.720* | 0.345* | 0.615* | 0.548* | 0.528* | 0.560* | 0.593* | 0.136 |

site of high dredging intensity the effects of dredging are still discernible on the composition of sediments and fauna even 6 years after cessation. This is in direct contrast to a body of case studies which together suggest that substantial progress towards restoration of the fauna could be expected within 2−4 years following cessation of marine sand and gravel extraction (Millner *et al.*, 1977; Kenny *et al.*, 1998; Desprez, 2000; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000; ICES, 2001). This discrepancy between the Area 222 data and other studies may reflect differences in the magnitude of dredging disturbance, since many of the studies reported in the literature have been concerned with the effects of relatively short-lived dredging campaigns (Kenny *et al.*, 1998; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000), whereas Area 222 was dredged repeatedly over a 25-year period. Indeed, evidence from the current study suggests that the nature and speed of recolonization is affected by the intensity of dredging. This may also suggest that undisturbed deposits between dredged furrows provide an important source of colonizing species (Newell *et al.*, 1998), allowing recolonization to proceed more rapidly in less heavily dredged sediments than in areas of intensive dredging. The discrepancy between our findings and those reported in the literature is also likely to reflect differences in the sediment composition at the dredging sites. Sites with sediments containing a higher gravel content typically support a richer assemblage than sandy substrata, and therefore it is to be anticipated that such sites will require a longer time scale for successful regeneration of benthic assemblages (see later).

Local environmental factors are also likely to affect the rate of re-establishment of benthic fauna and in particular the hydrodynamics of a site determine the sedimentary characteristics of an area and will ultimately be responsible for determining broad-scale community patterns (Warwick and Uncles, 1980; Hall, 1994; Rees *et al.*, 1999). It is therefore apparent that any changes in the status of benthic assemblages in areas which have been subjected to extraction will need to be referenced against both variations in particle size and the hydrodynamic regime. Based on the water depth, tidal current, and wave data (Admiralty data), Area 222 is considered to be a site of “moderate” energy. This conclusion is important since it implies that many years, possibly decades, will be required for re-establishment of benthic assemblages in sites classed as “low energy”.

## The recolonization of dredged sites

From studies of dredged sites (Cressard, 1975; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000; Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000; Van Dalfsen and Essink, 2001; Boyd *et al.*, 2003) and from observations following defaunation as a consequence of storm disturbance (Rees *et al.*, 1977), a general pattern of recolonization is emerging (see also ICES, 2001). The first stage involves the settlement of a few opportunistic species, which are able to take advantage of the dredged and sometimes unstable sediments (Hily, 1983; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000; Van Dalfsen *et al.*, 2000; Van Dalfsen and Essink, 2001). Recolonization can either be by adults or larvae from the surrounding area if the sediments of the disturbed area are similar to the original substrata (Cressard, 1975) or by larvae from more distant sources if the sediment is markedly different (Santos and Simon, 1980; Hily, 1983). These species can substantially increase the overall abundance and the numbers of species during the early stages of post-dredging recolonization (Hily, 1983; López-Jamar and Mejuto, 1988; Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000; Van Dalfsen *et al.*,

Table 7. Results from SIMPER analysis of macrofauna data from Area 222 (all taxa excluding colonial species, fourth root transformed), listing the main characterizing species from samples subject to differing levels of dredging impact from 2000 to 2002. Average abundance, average similarity and the % contribution to the similarity made by each characterizing species is shown. Also listed is the cumulative percentage and the overall average similarity between replicate samples from within each group.

| Group | Taxonomic group | Average abundance | Average similarity | % Contribution | Cumulative % | Overall average similarity % |
|---|---|---|---|---|---|---|
| HIGH '00 | *Glycera lapidum* (agg.) | 1.8 | 7.98 | 26.90 | 26.90 | 29.7 |
| | *Sphaerosyllis taylori* | 2.4 | 4.29 | 14.47 | 41.37 | |
| LOW '00 | *Lumbrinereis gracilis* | 11.0 | 3.45 | 6.54 | 6.54 | 52.73 |
| | *Exogone verugera* | 5.4 | 2.80 | 5.30 | 11.84 | |
| | *Glycera lapidum* (agg.) | 5.2 | 2.79 | 5.28 | 17.13 | |
| | *Notomastus* sp. | 4.8 | 2.65 | 5.02 | 22.15 | |
| | Ophiuroidea (juv.) | 3.6 | 2.64 | 5.01 | 27.16 | |
| | *Polycirrus* spp. | 4.6 | 2.51 | 4.76 | 31.92 | |
| | *Spiophanes bombyx* | 2.8 | 2.28 | 4.32 | 36.24 | |
| | *Ascidiidae* (juv.) | 2.6 | 2.26 | 4.29 | 40.53 | |
| REF1 '00 | *Pomatoceros lamarcki* | 48.6 | 3.81 | 7.66 | 7.66 | 49.70 |
| | *Pisidia longicornis* | 22.2 | 3.30 | 6.64 | 14.30 | |
| | *Lumbrinereis gracilis* | 16.4 | 3.28 | 6.60 | 20.90 | |
| | *Polydora* sp. | 9.8 | 2.84 | 5.71 | 26.61 | |
| | *Amphipholis squamata* | 7.4 | 2.35 | 4.72 | 31.33 | |
| | *Sabellaria spinulosa* | 5.2 | 2.24 | 4.51 | 35.84 | |
| | *Harmothoe* spp. | 6.8 | 2.04 | 4.10 | 39.94 | |
| | *Sphaerosyllis taylori* | 2.8 | 1.94 | 3.90 | 43.85 | |
| HIGH '01 | *Spisula* sp. (juv.) | 3.9 | 8.49 | 31.21 | 31.21 | 27.20 |
| | *Glycera lapidum* (agg.) | 2.2 | 8.39 | 30.82 | 62.03 | |
| LOW '01 | *Lanice conchilega* | 30.4 | 4.38 | 8.83 | 8.83 | 49.65 |
| | *Pisidia longicornis* | 8.9 | 3.08 | 6.20 | 15.03 | |
| | *Amphipholis squamata* | 5.5 | 2.98 | 6.01 | 21.04 | |
| | *Harmothoe* spp. | 4.4 | 2.74 | 5.53 | 26.56 | |
| | *Echinocymanus pusillus* | 4.9 | 2.71 | 5.47 | 32.03 | |
| | *Lumbrineris gracilis* | 3.6 | 2.68 | 5.40 | 37.43 | |
| | *Pomatoceros lamarcki* | 4.6 | 2.26 | 4.55 | 41.98 | |
| REF1 '01 | *Pisidia longicornis* | 55.0 | 4.21 | 8.24 | 8.24 | 51.13 |
| | *Lanice conchilega* | 25.4 | 3.61 | 7.07 | 15.31 | |
| | *Pomatoceros lamarcki* | 30.2 | 3.55 | 6.95 | 22.26 | |
| | *Serpulidae* | 14.80 | 3.36 | 6.57 | 28.83 | |
| | *Amphipholis squamata* | 6.0 | 2.64 | 5.17 | 34.00 | |
| | *Gibbula* sp. | 3.6 | 2.30 | 4.49 | 38.49 | |
| | *Harmothoe* spp. | 5.6 | 2.24 | 4.38 | 42.86 | |
| REF2 '01 | *Lanice conchilega* | 83.6 | 4.26 | 7.61 | 7.61 | 56.03 |
| | *Pomatoceros lamarcki* | 38.4 | 3.52 | 6.29 | 13.90 | |
| | *Serpulidae* | 12.6 | 2.73 | 4.87 | 18.77 | |
| | *Lumbrineris gracilis* | 10.8 | 2.53 | 4.52 | 23.28 | |
| | *Pisidia longicornis* | 18.6 | 2.44 | 4.35 | 27.63 | |
| | *Scalibregma inflatum* | 9.0 | 2.44 | 4.35 | 31.98 | |
| | *Lagis koreni* | 5.6 | 2.10 | 3.75 | 35.73 | |
| | *Cerianthus lloydi* | 4.4 | 2.02 | 3.60 | 39.34 | |
| | *Gibbula* sp. | 6.0 | 2.01 | 3.59 | 42.93 | |
| HIGH '02 | *Spisula* sp. (juv.) | 6.6 | 7.18 | 23.68 | 23.68 | 30.30 |
| | Nemertea | 2.8 | 4.74 | 15.64 | 39.33 | |
| | *Glycera lapidum* (agg.) | 1.6 | 3.27 | 10.80 | 50.13 | |
| LOW '02 | *Pisidia longicornis* | 43.0 | 3.98 | 6.89 | 6.89 | 57.76 |
| | *Pomatoceros lamarcki* | 35.5 | 3.78 | 6.54 | 13.43 | |
| | *Sepulidae* | 8.7 | 2.62 | 4.54 | 17.97 | |

Table 7 (*continued*)

| Group | Taxonomic group | Average abundance | Average similarity | % Contribution | Cumulative % | Overall average similarity % |
|---|---|---|---|---|---|---|
| | *Amphipholis squamata* | 7.8 | 2.60 | 4.51 | 22.48 | |
| | *Lumbrineris gracilis* | 7.5 | 2.52 | 4.37 | 26.85 | |
| | *Scalibregma inflatum* | 7.3 | 2.39 | 4.13 | 30.99 | |
| | *Caulleriella alata* | 7.6 | 2.38 | 4.11 | 35.10 | |
| | *Notomastus* | 6.3 | 2.14 | 3.70 | 38.81 | |
| | *Echinocyamus pusillus* | 4.5 | 2.09 | 3.63 | 42.43 | |
| REF1 '02 | *Pisidia longicornis* | 155.4 | 4.58 | 8.73 | 8.73 | 52.45 |
| | *Pomatoceros lamarcki* | 25.0 | 2.82 | 5.37 | 14.10 | |
| | *Amphipholis squamata* | 15.0 | 2.75 | 5.24 | 19.34 | |
| | *Lumbrineris gracilis* | 12.8 | 2.46 | 4.69 | 24.03 | |
| | *Serpulidae* | 6.0 | 2.18 | 4.16 | 28.19 | |
| | *Cheirocratus* sp. | 3.8 | 2.02 | 3.85 | 32.04 | |
| | *Laonice bahusiensis* | 4.2 | 1.96 | 3.73 | 35.78 | |
| | *Corophium sextonae* | 4.0 | 1.81 | 3.44 | 39.22 | |
| | *Caulleriella alata* | 5.6 | 1.73 | 3.31 | 42.53 | |
| REF2 '02 | *Pomatoceros lamarcki* | 27.0 | 3.35 | 6.62 | 6.62 | 50.61 |
| | *Lumbrineris gracilis* | 12.4 | 2.91 | 5.76 | 12.38 | |
| | *Pisidia longicornis* | 28.4 | 2.72 | 5.37 | 17.75 | |
| | *Serpulidae* | 9.6 | 2.69 | 5.31 | 23.06 | |
| | *Ampelisca spinipes* | 7.2 | 2.54 | 5.01 | 28.07 | |
| | *Laonice bahusiensis* | 3.6 | 2.05 | 4.05 | 32.12 | |
| | *Galathea intermedia* | 3.4 | 2.02 | 3.99 | 36.11 | |
| | *Amphipholis squamata* | 5.8 | 1.95 | 3.86 | 39.97 | |
| | *Scalibregma inflatum* | 3.8 | 1.92 | 3.80 | 43.77 | |

2000). A second phase is characterized by a reduced community biomass which can persist for a number of years (Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998; Desprez, 2000). There is a natural expectation that biomass will remain reduced, while new colonizers "grow on" to maturity comparable with the pre-dredging age/size profile (Rees, 1987; Van Dalfsen and Essink, 2001). Furthermore, a reduced biomass may also be caused by the abrasive effects of increased sediment (mainly sand) inhibiting the growth and survivorship of epifauna such as hydroids and bryozoans. Paradoxically, it is this sandy sediment that is also responsible for the infilling of dredge tracks (Kenny *et al.*, 1998; ICES, 2001; Limpenny *et al.*, 2002), which in the longer term may promote physical stability. Over time, it may be expected that, at some sites, the bedload transport will approach the pre-dredged equilibrium, allowing the restoration of community biomass (Kenny *et al.*, 1998). A similar model of response has been represented schematically by Hily (1983) and includes a further stage in which opportunists are replaced by a greater number of species. It was suggested that this replacement was the result of increasing levels of interspecific competition. However, this model was based on observations following the dredging of a sandy mud (Hily, 1983), and further evidence is required to establish whether such oscillations occur in more stable gravel habitats during the latter stages of succession. Evidence from Area 222 suggests that, where there are significant changes to the topography and composition of the sediments as a result of dredging activity, the maintenance of a biological community, over prolonged periods, at an early developmental stage can be expected.

## Framework for future studies

As yet, coordinated studies on a wide geographical scale investigating the physical and biological status of commercial aggregate extraction sites in the UK and elsewhere are limited (Van Dalfsen *et al.*, 2000). One consequence of the limited available information on the effects on the benthos of marine aggregate extraction is the difficulty it creates for the establishment of reliable empirical models for predictive purposes. A further difficulty in generalizing about the effects of extraction is the variability in both the dredging history and the particular dredging practices to which different extraction sites are exposed, i.e. a typology of dredging disturbance does not exist. Consequently, when seeking to develop and then apply predictive models, generalizations about the effects of marine aggregate extraction must be qualified by local information regarding the nature of dredging activity and the conditions under which extraction activity occurs. Based on existing evidence, however, the two most

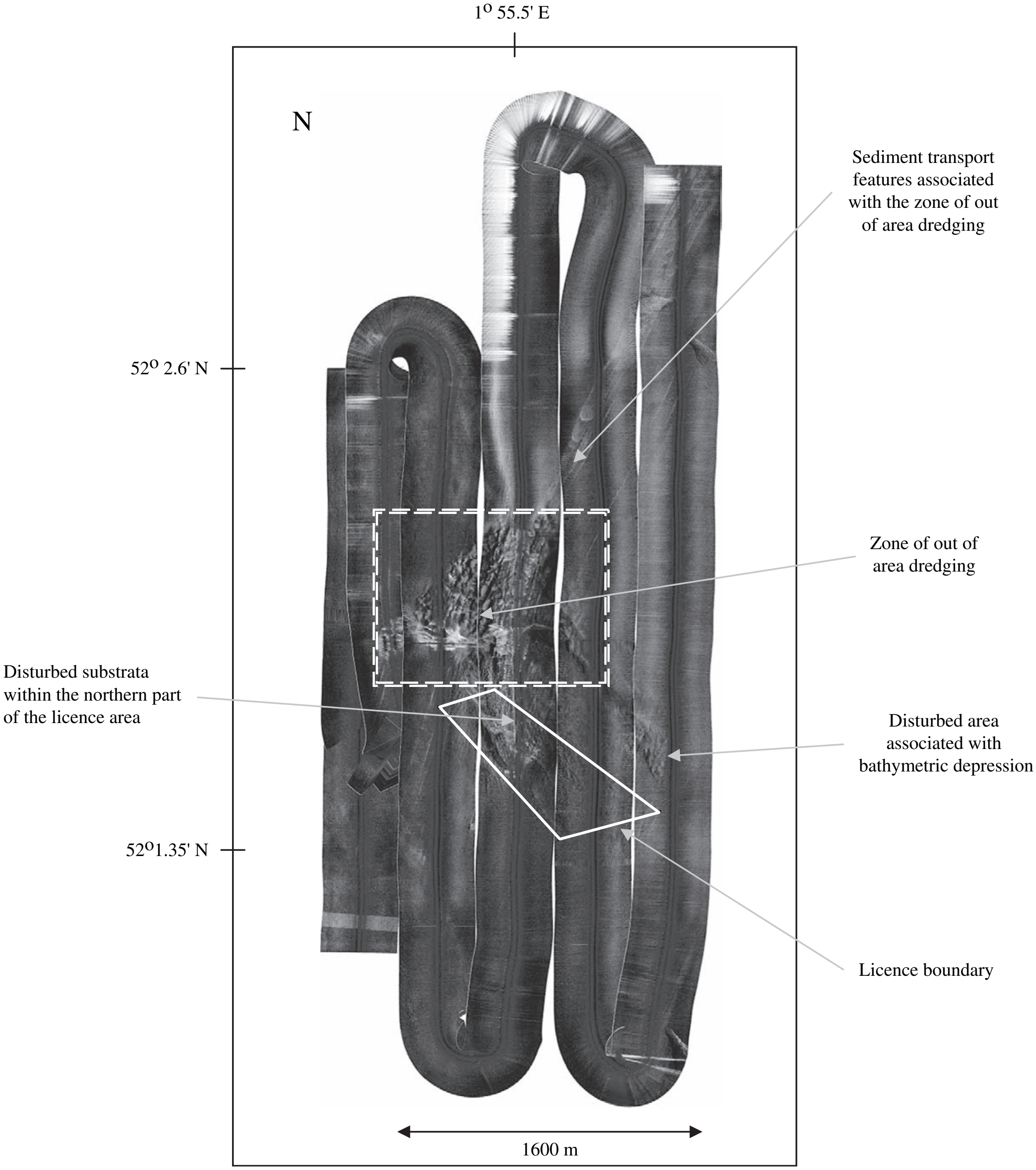


Figure 8. A sidescan sonar mosaic derived from a survey undertaken in 2002 showing the distribution of substrata within and surrounding the former extraction site at Area 222, southern North Sea.

commonly encountered scenarios following marine aggregate extraction in the UK are:

(i) sites where the substratum has changed from a sandy gravel to a gravelly sand;
(ii) sites where the substratum has remained unchanged.

This is not to exclude the possibility of other consequences such as the exposure of clay depending on local circumstances (Boyd *et al.*, 2003). In the first of the scenarios, there are a number of ways in which alterations to the sediment as a consequence of dredging could result. These include, but may not be limited to, the exposure of an underlayer of finer

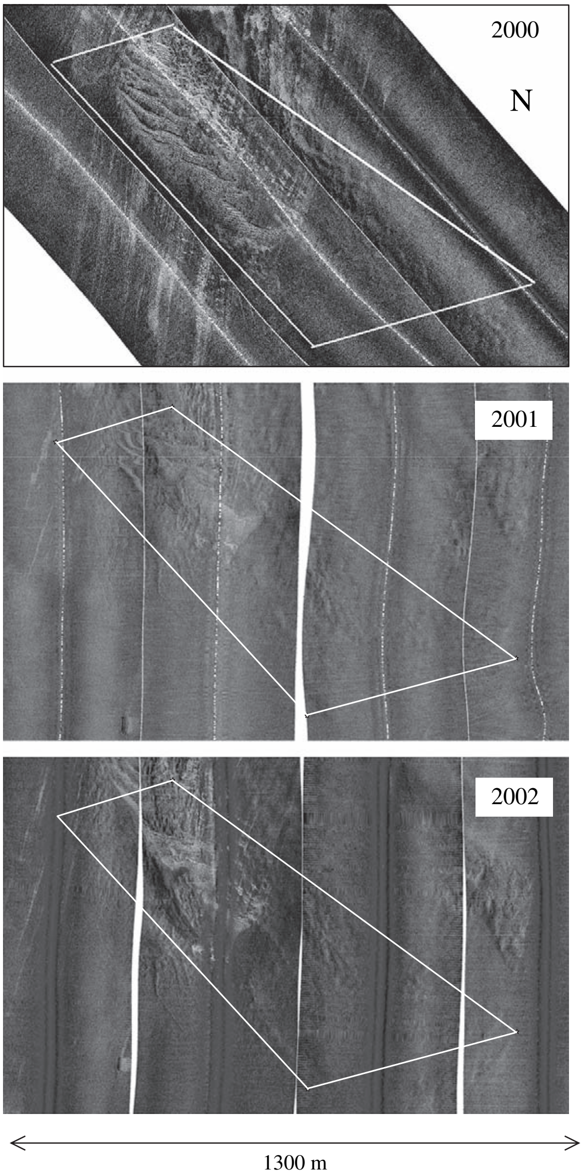


Figure 9. Sidescan sonar mosaics of the relinquished extraction site, collected in 2000, 2001, and 2002. The boundary of the former extraction licence is outlined in white.

sediments, discharge of finer sediments from spillways (Hitchcock and Drucker, 1996; Van Dalfsen *et al.*, 2000) or screening and the trapping of bedload in dredged furrows (Desprez, 2000; Sardá *et al.*, 2000; ICES, 2001). The degree of change appears to depend both on the local circumstances (Desprez, 2000; Van Dalfsen *et al.*, 2000; Boyd and Rees, 2003), and on the magnitude of perturbation i.e. differences in the intensity, type of dredging, or length of extraction period (Van Dalfsen *et al.*, 2000; Boyd *et al.*, 2003; Boyd and Rees, 2003). The colonizing fauna also appear to reflect this change to the substrata, through a shift in the proportions of sandy vs. gravelly fauna (Desprez, 2000). Accompanying this, it is postulated that there would be a net decline in biomass. This model of response is portrayed schematically in Figure 11. A similar model of response could account for changes at some sand extraction sites where the seabed substrata have changed from coarse to fine sands (Sardá *et al.*, 2000; Van Dalfsen *et al.*, 2000).

In the second scenario, sediments present at the seabed following the cessation of marine aggregate extraction are similar to those which existed prior to disturbance, i.e. sandy gravels. This scenario accords with current expectations regarding seabed status following licensed dredging and is consistent with the management aim of ensuring that the seabed environment is left in a comparable physical condition to that prevailing prior to the onset of dredging i.e. with a similar sediment type and evenness profile. From the limited available data concerning the effects of marine gravel extraction (Kenny and Rees, 1994, 1996; Kenny *et al.*, 1998), it is reasonable to postulate that the fauna recolonizing such sites will follow classical successional dynamics (e.g. Grassle and Sanders, 1973). Indeed, this scenario was postulated in connection with the disposal of dredged coarse material arising from a port expansion or channel deepening (see Anon., 1996). Although such simplified models require further validation and/or refinement, they provide a useful framework for evaluating the outcome of post-cessation recolonization studies and recovery rates and eventually could provide a reliable predictive capability. A body of case studies on the consequences of marine aggregate extraction over sufficiently long time scales from sites exposed to commercial extraction practices is therefore required to underpin the derivation of reliable and scientifically credible models of response. Such a need applies equally to many other human activities which take place in the marine environment.

## Conclusions

Many of the field studies reported in the literature are the results of investigations on the impacts of short-term dredging events, and these have proved useful in determining the rates and processes leading to benthic re-establishment following aggregate extraction. From such studies and those undertaken at sites exploited for commercial interests, a general pattern of response to marine aggregate extraction is emerging. This needs to be tested to establish its general validity in all environments, particularly in areas which have been exposed to industrial scale dredging operations over many years. From such work, it is clear that re-establishment of a community similar to that which existed prior to dredging can only be attained if the topography and original sediment composition are restored (for a contrary view, see Seiderer and Newell, 1999). Should physical stability of the sediments not be attained, however, it is hypothesized that communities will remain at an early developmental stage.

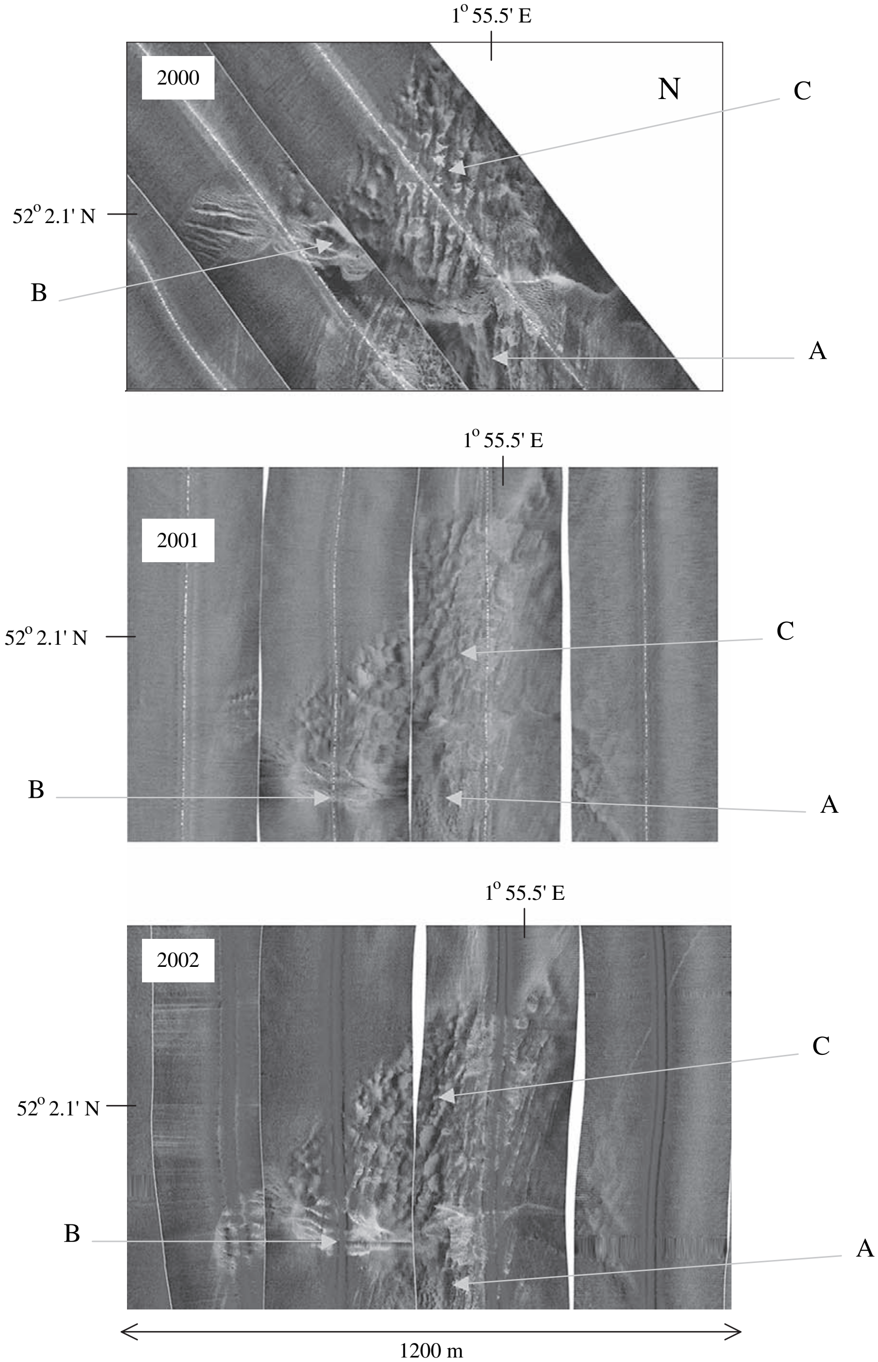


Figure 10. Sidescan sonar images collected between 2000 and 2002 of the disturbed area of seafloor to the north of Area 222, A) evidence of suction trailer dredging, B) large sand waves, C) evidence of static suction dredging.


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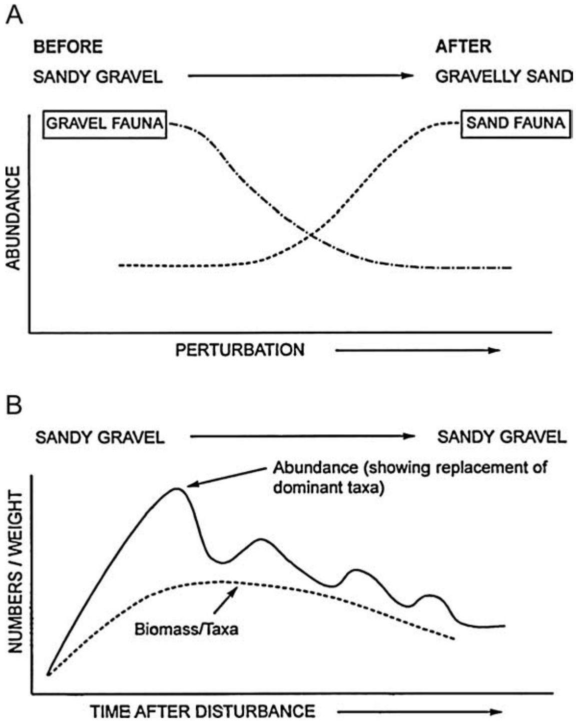


Figure 11. A) Simplified diagram of changes in the proportions of gravelly fauna in response to a change in sediment type as a consequence of marine aggregate extraction. B) Simplified model of changes in the benthos after the cessation of marine aggregate extraction.

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